NASA-TM-111267

AIAA 95-3610
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AIAA 1995 Space Programs and Technologies Conference
September 26-28, 1995/Huntsville, AL

OPTIMAL TECHNOLOGY INVESTMENT STRATEGIES FOR A REUSABLE LAUNCH VEHICLE

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Abstract

Within the present budgetary environment, developing the technology that leads to an operationally efficient space transportation system with the required performance is a challenge. The present research focuses on a methodology to determine high payoff technology investment strategies. Research has been conducted at Langley Research Center in which design codes for the conceptual analysis of space transportation systems have been integrated in a multidisciplinary design optimization approach. The current study integrates trajectory, propulsion, weights and sizing and cost disciplines where the effect of technology maturation on development cost of a single stage to orbit reusable launch vehicle is examined. Results show that the technology investment prior to full-scale development has a significant economic payoff. The design optimization process is used to determine strategic allocations of limited technology funding to maximize the economic payoff.

Nomenclature

ATP	Authority to Proceed
ATS	Access to Space
CER	Cost Estimating Relationship
CONSIZ	Configuration Sizing Program
DC	Development Cost
ECD	Electrical Conversion and Distribution
ISS	International Space Station
MDO	Multidisciplinary Design Optimization
NASA	National Aeronautics and Space Administration
OMS	Orbital Maneuvering System
POST	Program to Optimize Simulated Trajectories
RCS	Reaction Control System
RLV	Reusable Launch Vehicle
SSTO	Single Stage To Orbit
TC	Technology Cost
TPS	Thermal Protection System
TRL	Technology Readiness Level

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Introduction

For several years, NASA has been studying Earth-to-Orbit transportation options with the goal of reducing the cost of access to space.[1-4] The Access to Space Study [5] concluded that a fully reusable system utilizing "leapfrog" technology was the optimal method to achieve the goals of low cost and increased safety and reliability. It was also concluded the most desirable path toward the development of an advanced technology fully reusable rocket vehicle was a focused technology maturation program where the enabling and enhancing technologies are developed and demonstrated prior to beginning a full-scale development program. This direction is currently being taken under the X-33 Cooperative Agreements between NASA and industry. Critical to the success of this program is a clear understanding of the relationship between technology, design and cost.

The synthesis of a launch vehicle concept is a multidisciplinary process involving geometry, aerodynamics, propulsion, structures, materials, subsystems, weights and sizing, heating, performance, operations, cost, etc. In order to make informed technology decisions early in the design process, a streamlined capability for rapid analysis of candidate concepts is needed. Research has been conducted at NASA Langley Research Center in which design codes for the conceptual analysis of space transportation systems have been integrated and a multidisciplinary optimization (MDO) approach has been applied.[6,7] The MDO framework has been applied to reusable launch vehicle concepts to examine a variety of conceptual and configuration trade analyses. More recently, the impact of including cost equations into this conceptual design process has been explored.[8,9] The present research uses the MDO framework to quantify the effect of technology maturation on development costs.

Reusable Launch Vehicle Technologies

In accordance with national space transportation policy, a Reusable Launch Vehicle (RLV) program has been initiated with the goal of dramatically reducing the cost of access to space. The technology maturation process leading to the eventual development of an SSTO design with sufficient robustness for operational efficiency is an essential component of this program. A five-year technology program that allows the vehicle technologies to be matured prior to initiation of full-scale development is presently underway.

The RLV technology program is based on the technology plan set forth in the Access to Space Study.[10] Under this study, a technology assessment was performed by technology working groups with expertise in the various disciplinary areas. To cover a broad spectrum of options, technologies for three classes of reusable vehicle concepts were assessed: an all rocket SSTO; an airbreathing/rocket SSTO; and an airbreathing/rocket two-stage to orbit (TSTO).[11] The detailed assessment includes the current readiness status, a list of technology tasks, level of technical risk, level of program criticality, priority, and estimates of cost and schedule for each candidate technology. The NASA Technology Readiness Level (TRL) scale (Figure 1) was used as the measure of technology maturity. Funding requirements are based on the estimated cost required to advance the technologies from their current assessed levels to NASA TRL 6 within five years. This assessment was used as a reference in the present investigation.

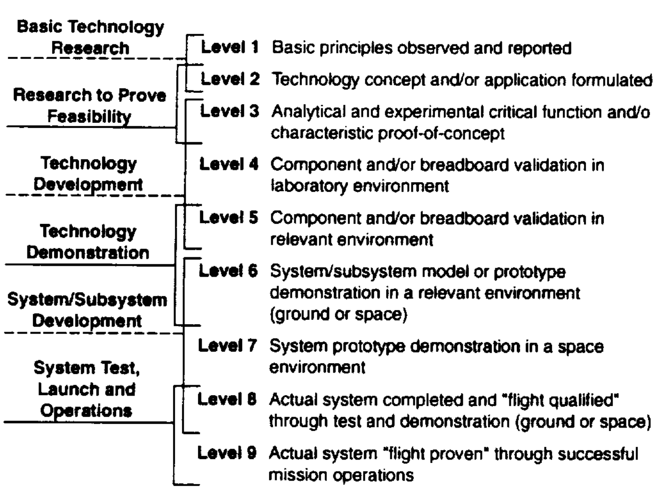

Figure 1. NASA technology readiness levels.

Problem Definition

The degree of success of the technology program will have a strong effect on the cost of the program to follow. The effect of technology maturation at the initiation of vehicle development can be shown to have a significant effect on the development cost and schedule. Using the PRICE-H[12] cost model, three funding profiles were generated for a reference RLV concept reflecting differences in development programs (Figure 2). PRICE-H is a multivariate model that utilizes engineering and design variables to generate integrated cost and schedule predictions. To generate the data shown in Figure 2, the maturity level of technologies was varied, holding all other design and programmatic variables constant. The total development cost in fixed year dollars for each program is the area under each curve. In program A, technologies are matured to TRL 6 prior to start of development. Program B starts the development program at current TRL levels, without the benefit of a technology maturation program, resulting in a significant increase in cost and schedule. Program C starts development at current TRL levels, but tries to achieve an accelerated schedule equal to the duration predicted under Program A. All technologies are matured, but at different rates and on different schedules.

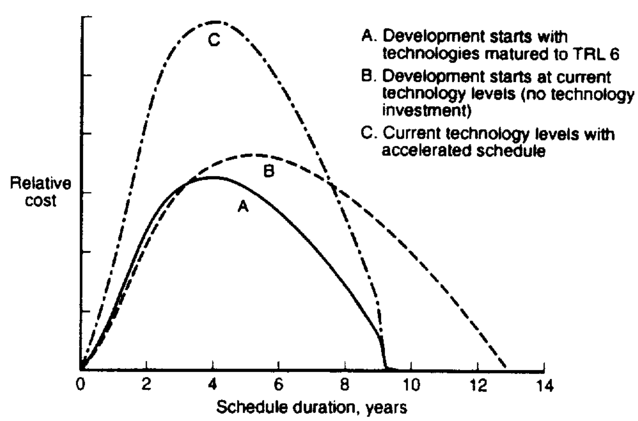

Figure 2. Impact of technology maturation.

The above analysis demonstrates the dynamic relationship between technology, cost and schedule. Next, the trade between the dollars spent on the technology program, termed technology investment, and the resultant decrease in program cost and schedule is examined.

The performance and operability requirements of a next generation space transportation system require advancements in multiple technologies areas regardless of the concept eventually selected. Several core technologies were identified as essential for the development of any of the three options studied under the ATS study: reusable cryogenic tanks, low-maintenance TPS, autonomous flight control, operations enhancement technologies, vehicle health management, and lightweight structures. In addition, enabling technologies unique to each class of vehicle concept were identified, i.e., main propulsion.[10] The cost of maturing the individual technologies varies, as does the development cost of the vehicle subsystems in which the technology is utilized. Each technology has a different degree of payoff to the vehicle in terms of development cost, schedule, and performance.

The problem addressed here is to quantify the potential payoffs to the vehicle in terms of total development cost based on the trade between the timing of technology development in the individual technologies and the resultant impact on contributing subsystem development costs. Once quantified, high-payoff technology investment strategies can be determined. A multidisciplinary design optimization approach is used for this determination.

Multidisciplinary Design Optimization

Over the last several years, a multidisciplinary design framework has been developed at Langley Research Center for the analyses of vehicle systems. Numerous optimization approaches and disciplinary combinations have been applied to a variety of launch and reentry problems.[6,7] Improvements have been achieved using the MDO approach over other methods which required the generation of many more design points in order to analyze the various design options and sensitivities. Recently, cost algorithms have been integrated into this framework.[8, 9]

The design of a representative SSTO RLV with a selected set of technologies is used in the present study. The RLV is a dual-fueled rocket sized to deliver and return a 25,000-lb. payload to the International Space Station (ISS). The launch is assumed to originate at the Eastern Test Range at the Kennedy Space Center and the ISS is assumed to be in a 220-n. mi. circular orbit with a 51.6 degree inclination. The design of the vehicle incorporates several of the technologies assessed in the Access to Space study. Technologies include composite primary and secondary structures, advanced carbon-carbon hot structures, aluminum lithium reusable tanks, advanced thermal protection system, tripropellant advanced main propulsion, integrated RCS/OMS auxiliary propulsion, high-density fuel cells, electromechanical actuation, vehicle health monitoring and management, and autonomous flight controls. This vehicle is more completely described in Stanley, et al.[13]

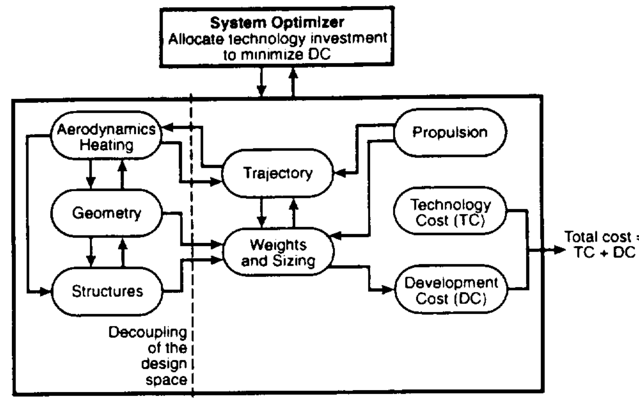

Figure 3. Multidisciplinary design optimization framework..

A design framework linking performance, weights and sizing, propulsion, and cost disciplines was used. (Figure 3). An existing vehicle geometry, structural concept and aerodynamic database were used to complete the analyses but were not directly integrated into the MDO framework.

Vehicle performance was determined by numerically integrating the three degree-of-freedom equations of motion with the use of the Program to Optimize Simulated Trajectories (POST).[14] POST is used to calculate the in-flight and terminal constraints and to compute the vehicle mass ratio and required propellant fractions, which are required inputs for the weights and sizing analysis. Inflight constraints include a normal force limit and 3-g acceleration limit. Propulsion system parametrics supplied by Pratt & Whitney, based on modification of a proposed Russian RD-701 dual-fuel engine, were used for this analysis. The engine is fitted with a dual position nozzle which has an extension limit such that a maximum 2:1 increase in exit area results. The dry weight of the vehicle is determined using the Configuration Sizing program (CONSIZ). CONSIZ requires weight estimating relationships specific to a vehicle composition and technology set, along with other inputs such as geometry, propellant densities, and mission information, and iteratively calculates weight and size breakdowns based on the mass ratio supplied by POST.

Two sets of cost estimating relationships (CERs) were developed for this analysis and integrated with the above design codes. The first is a set of technology cost relationships that calculate the amount of dollar investment incurred as the technology progresses from its initial TRL to higher TRLs. There are nine equations, one for each technology area corresponding to vehicle subsystems: avionics, composite structures, electromechanical actuation, electrical conversion and distribution (ECD), auxiliary propulsion (OMS/RCS), prime power source, main propulsion, aluminum lithium propellant tanks and thermal protection system (TPS). The cost of each technology is summed to determine the total technology cost (TC). A linear relationship was assumed for each equation. These technology cost relationships are based on the estimates documented in the ATS study.[10]

A second set of cost relationships was need to complete the analysis. A set of vehicle-specific nonlinear CERs consistent with the weight breakdown structure (WBS) used in CONSIZ was derived parametrically to predict development cost as a function of weight, subsystem complexity, and technology readiness level. CERs for subsystems not utilizing an advanced technology, such as landing gear, were included to obtain a total vehicle cost. Development cost (DC) is defined in this analysis to be the cost of designing and developing the vehicle hardware under a full-scale development program. This definition of development cost includes the cost elements directly related to the design and technology variables contained in this study. Cost elements such as program management, fees, reserves, software and other programmatic costs are not included in the design loop. For the purpose of this analysis, these other cost elements are considered independent of the design trades over which the optimization occurs.

The four disciplines were integrated sequentially and compatibility constraints were used to ensure consistency across the disciplinary models. The efficiency and convergence properties of this approach have been demonstrated on a similar problem.[6] Optimization was performed using NPSOL, a sequential quadratic programming algorithm developed at Stanford University.[15]

The problem is formulated as follows: select the technology readiness levels, vehicle and trajectory design variables to minimize development cost such that the vehicle reaches its orbital destination subject to a variety of flight mechanics and vehicle system constraints while remaining within the technology cost limit.

Within the design space described above, a major trade being performed is on the allocation of a fixed amount of technology investment dollars among the nine technology areas. The optimization process seeks to allocate the fixed funding level in the technology cost equations so that technologies are sufficiently advanced prior to authority to proceed (ATP) to minimize development cost. The time progression of maturing the technologies is altered, but all technologies ultimately advance to a matured state. The technologies not advanced at an accelerated pace during the technology program are assumed to have sufficient time to mature during the development phase.

Proposed technology advancements not directly related to specific vehicle subsystems, such as aerosciences and operations, are assumed independent of development cost and therefore not included in this analysis. It is assumed advancement of these enabling technologies would proceed independently to meet life cycle objectives. Therefore, results shown in this paper do not represent a full focused technology program.

Results

For comparison purposes, a scenario in which no technology maturity occurs prior to the authority to proceed (ATP) to full-scale development was considered (Figure 4). In this case, vehicle development proceeds at current TRLs for all subsystems technologies. Since the technologies are insufficiently advanced at the start of development, maturation occurs under the development program. Development costs are at their maximum level but no technology costs are incurred. The sum of the technology cost and development cost is denoted total relative cost and is used as the baseline for comparison (100%).

Next, the program outlined under the Access to Space study, where all vehicle technologies are brought to TRL 6 prior to ATP is considered. This requires an up-front allocation of technology investment funding. The technology investment allocation and TRLs at ATP are shown in Figure 5.

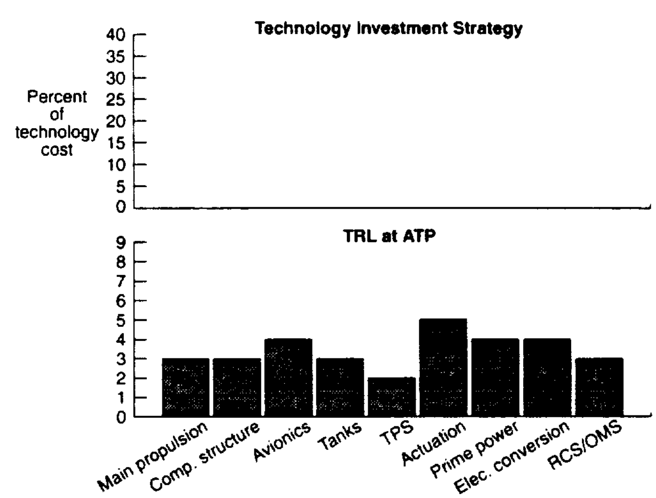

Figure 4. No technology investment.

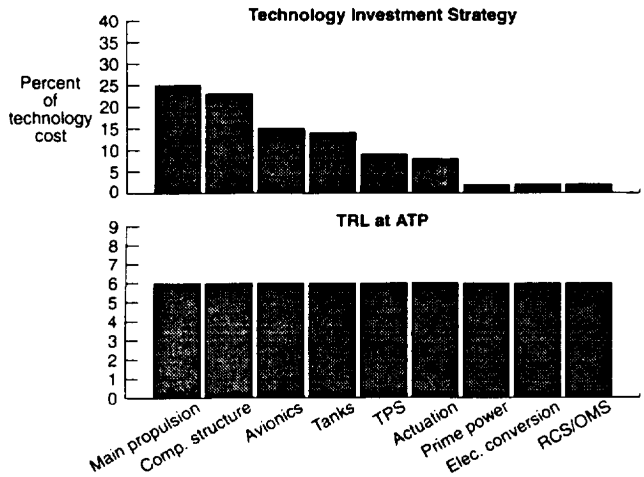

Figure 5. ATS technology plan. All technologies matured to TRL 6 prior to start of development.

The technology investment strategy is defined as the percentage of technology investment funds allocated to specific subsystem technologies. The TRLs at ATP are the anticipated technology readiness level reached by each technology prior to start of development based on the technology funding allocated. The ATS technology investment strategy results in a relative total cost of 57% of the baseline, a significant payoff.

Bringing all technologies to a TRL 6 prior to ATP was a groundrule of the ATS study. While desirable from a technological perspective, it is not clear that this represents an optimum strategy based on cost. The next case considers modifying this program constraint to observe whether further cost improvement can be achieved. The MDO framework described above was used to optimize the ATS technology funding level. This strategy is termed the optimized ATS case and results in a total relative cost of 47% of the baseline (Figure 6). This represents an 18% improvement over constraining the TRLs to 6.

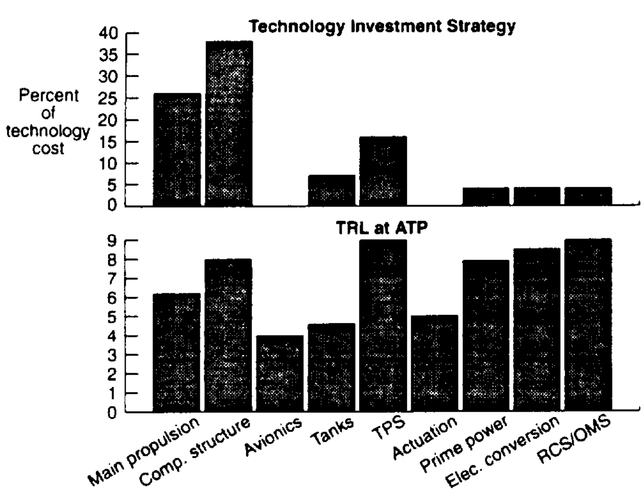

Figure 6. Optimized technology program.

Two additional scenarios were examined. First, an arbitrary 100 million dollars was added to the technology investment funding (Figure 7). This resulted in a relative total cost 44% of the baseline, representing a 6% improvement over the optimized Access to Space and a 23% improvement over the groundruled ATS. These improvements include the extra 100 M added to the program.

Secondly, the technology investment was reduced by the same amount (100M) as shown in Figure 8. In this case, a

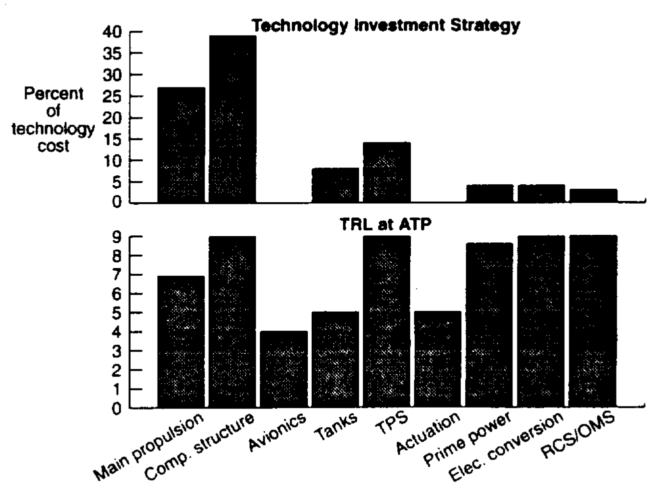

Figure 7. Increased technology program (+100M).

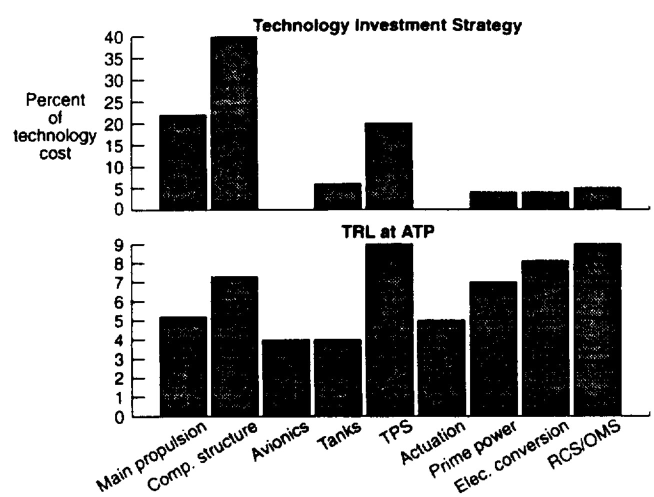

Figure 8. Decreased technology program (-100M).

total relative cost of 52% over the baseline was realized. This reduction in funding causes a cost increase of 11% over the optimized Access to Space. However, the total cost is still less than the case where all TRLs are brought to TRL 6 prior to ATP (9%) even though the technology investment is reduced. This implies that an improvement over the groundrule can be realized even with less up-front investment if the technology maturation strategy is optimized.

The optimization process takes into account the combined effect of the investment cost of each technology maturation, the relative cost contribution of the subsystem to the total vehicle development, and the development cost sensitivity to the TRL at ATP. For example, Figure 5 shows that main propulsion is the most expensive technology to mature, taking 25% of the investment funding to advance three levels (from TRL 3 to TRL 6). However, the main propulsion system is highly sensitive to changes in TRL and accounts for 28% of the vehicle dry weight and 27% of the development cost when development starts with all technologies at TRL 6. Therefore, a high investment level is maintained in the optimized cases, ranging from 22-28%, in order to minimize the effects of insufficiently maturing the technology. In contrast, avionics accounts for approximately 1% of the vehicle dry weight and 4% of the development cost at TRL 6. The payoff in terms of the total system is less dramatic for a relatively high investment cost.

In addition to main propulsion, technologies are advanced beyond TRL 6 in composite structures, TPS, prime power, ECD and RCS/OMS propulsion. There is a high payoff for composite structures and TPS because these two systems account for a large proportion of the vehicle costs. TPS is an especially high-leverage area because it is relatively

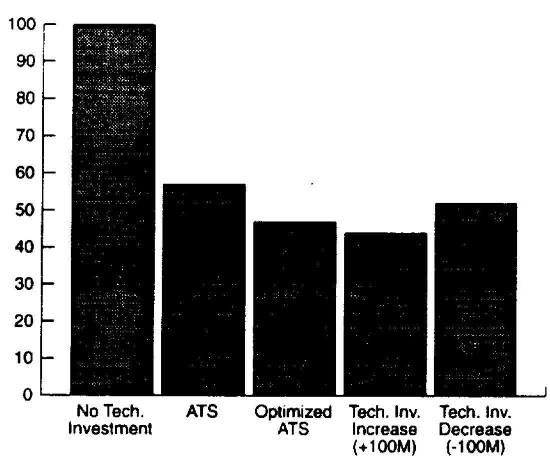

Figure 9. Relative cost summary.

inexpensive to mature. Prime power, ECD and RCS/OMS are not high-cost contributors, but advance beyond TRL 6 because the investment cost is low compared to the relative pay-back in terms of vehicle cost.

While some investment is made in the aluminum lithium cryogenic tanks to advance the technology beyond the current TRL 3, it only reaches TRL 4-5 before ATP. This result is based on the development cost impact and does not reflect the risk associated with reusable cryogenic tanks, an important consideration.

A summary comparison of the relative total costs of the five strategies considered in this study is shown in Figure 9.

Limitations of the Methodology

The direct insertion of cost algorithms into the "inner loop" of design allows for the consideration of cost in the earliest stages of concept development where there is the most opportunity for payoff. Efforts to expand the MDO capability are in progress. Improved codes are needed to more realistically model the interactions between the design parameters and cost, including schedule prediction and risk assessment. The present study does not capture the risk associated with technology advancement and the resultant impact on the vehicle design (i.e., weights, etc.), performance and cost. Other improvements, such as life cycle cost considerations, should be considered.

Conclusions

Based on the above analysis, it is clear that conducting a technology maturation program prior to full-scale development has a significant payoff. The magnitude of the payoff varies depending on the level of funding available for technology investment and the strategy used to allocate the funding to the various technology areas. With this analysis capability, flexibility can be exerted to accommodate budget or program changes without compromising system performance. The analysis could be greatly enhanced by an increase in the modeling capability to include risk and schedule considerations.

Summary

Cost is going to have to be a design consideration for future transportation systems. If cost can be considered during concept development, and even earlier in technology development, then the technologies to produce operationally-efficient vehicles will not be a barrier to the development of cost-efficient systems. This paper has demonstrated an application of an MDO approach that considers cost, weights and sizing, propulsion, and trajectory variables in an integrated analysis framework. Technology strategies were devised to determine an effective allocation of the early program dollars without compromising performance or operability objectives. The effectiveness of this approach has been demonstrated through a specific formulation that examines the effect of technology maturity on launch vehicle design and cost.

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